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Use of an Urban Intensity Index to Assess Urban Effects on Streams in Three Contrasting Environmental Settings

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Abstract.—To assess the effects of urbanization on assemblages (fish, invertebrate, and algal), physical habitat, and water chemistry, we investigated the relations among varying intensities of basin urbanization and stream ecology in three metropolitan areas: the humid northeastern United States around Boston, Massachusetts; the humid southeastern United States around Birmingham, Alabama; and the semiarid western United States around Salt Lake City, Utah. A consistent process was used to develop a multimetric urban intensity index (UII) based on locally important variables (land-use/land-cover, infrastructure, and socioeconomic variables) in each study area and a common urban intensity index (CUII) based on a subset of five variables common to all study areas. The UII was used to characterize 30 basins along an urban gradient in each metropolitan area. Study basins were located within a single ecoregion in each of the metropolitan areas. The UII, ecoregions, and site characteristics provided a method for limiting the variability of natural landscape characteristics while assessing the magnitude of urban effects. Conditions in Salt Lake City (semiarid climate and water diversions) and Birmingham (topography) required nesting sites within the same basin. The UII and CUII facilitated comparisons of aquatic assemblages response to urbanization across different environmental settings.

Introduction

Urbanization represents a complex environmental gradient that provides a framework for assessing changes in the physical, chemical, and biological characteristics of ecosystems (McDonnell and Pickett 1990). Numerous studies have documented specific physical, chemical, or biological responses to urbanization within a stream or among streams within a region (e.g., Wang et al. 2000; Paul and Meyer 2001; Walsh et al. 2001; Center for Watershed Protection 2003). Few studies have examined the physical, chemical, and biological characteristics to urbanization in contrasting geographic areas (Paul and Meyer 2001). The nature and magnitude of urban effects on streams vary widely, depending on the geographic area studied and the initial ecosystem conditions represented within it. Understanding the differences and similarities of how urbanization affects physical, chemical, and biological characteristics of streams across the United States is important for managing aquatic resources.

A gradient approach has been used to assess the effects of urbanization on geomorphic conditions and aquatic assemblages (e.g., Booth and Jackson 1997; Wang et al. 2000; Walsh et al. 2001; Fitzpatrick et al. 2004; Taylor et al. 2004). Understanding and comparing urban effects on streams and associated aquatic assemblages can be complicated by how urban influ-

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ences are quantified or defined (e.g., human population density, percent urban land, percent impervious area, etc.). In addition, the relations among population density, percent urban land, and percent impervious area in a basin may not be understood and depend on regional and historical differences in development of urban areas as well as natural factors such as climate, physiography, geological setting, vegetation types, and soils (Harding et al. 1998; Fitzpatrick et al. 2004). Thus, providing a comprehensive understanding of regional responses to urbanization that are comparable among different environmental settings requires multiple regional urban studies using a common design and sample collection techniques (Cuffney et al. 2005, this volume).

Most studies have used a single measure of urban intensity, such as population density, percent urban land, and percent imperviousness (Arnold and Gibbons 1996), to interpret responses to urbanization. Yoder and Rankin (1995), however, noted that interpretation of ecosystems effects could vary depending on which single measure was used to quantify urban effects. Although impervious area was commonly used to represent urban intensity (Arnold and Gibbons 1996), Karr and Chu (2000) suggested that impervious area alone does not account for all aspects of urbanization. Patterns of development within a metropolitan area are a function not only of the amount of developed land, but also of differences in infrastructure (e.g., roads, sewers, storm water drainage), human population, and socioeconomic (e.g., income, housing) characteristics (McMahon and Cuffney 2000). Multimetric indices have been used to describe the overall condition of complex systems (Karr 1981; Simon and Lyons 1994; Ward 1996; Karr and Chu 1999) and land-use intensities (Ometo et al. 2000; Morley and Karr 2002). A multimetric indicator of urban intensity combines individual condition measures that provide distinct information about the different dimensions of complex systems (McMahon and Cuffney 2000). This approach aids integration of multiple, commonly used sources of information about the urban landscapes, such as land-cover, infrastructure, population, and socioeconomic variables, into a single measure of urban intensity index (Cuffney et al. 2000; McMahon and Cuffney 2000).

In 2000, we initiated a series of studies that used a common design to examine the regional effects of urbanization on aquatic assemblages, physical habitat, and water chemistry in three metropolitan areas that represent contrasting environmental settings. These studies were conducted in the humid northeastern United States around Boston, Massachusetts; the humid southeastern United States around Birmingham, Alabama; and the semiarid western United States around Salt Lake City, Utah. This study was unique in its use of urban intensity indexes (UIIs) to select sites along urban gradients while minimizing differences in natural basin features and local disturbances within three markedly different climatic regions of the United States. The UII was intended to provide an a priori basis for ranking the relative intensity of urban development from low to high (McMahon and Cuffney 2000). A common urban intensity index (CUII) was also calculated using a subset of urban indicators common to all study areas to allow direct comparisons of urban intensities among regions. Once sites were selected, aquatic assemblages, physical habitat, and water chemistry were sampled using the same protocols so that these ecological responses to urbanization could be compared among study areas.

This paper describes the application of the urban intensity gradient design of McMahon and Cuffney (2000) across different environmental settings. The next four chapters (Cuffney et al. 2005; Meador et al. 2005; Short et al. 2005; Potapova et al. 2005; all this volume) compare ecological responses (habitat, algal, invertebrate, and fish) along the urban intensity gradients in three contrasting environmental settings.

Methods

Study Areas

Boston (BOS).—The BOS study area was in Massachusetts, New Hampshire, Maine, and Connecticut in the northeastern United States (Figure 1). The major metropolitan area is Boston, Massachusetts, with a 1992 population of 5.7 million (Flanagan et al. 1999). The study area is in the Northeastern Coastal Zone ecoregion (Omernik 1987), which is characterized by low hills, forests, cropland and pasture, and urban lands and inceptisol soils (Flanagan et al. 1999). Elevation ranges from about 6–61 m above sea level. The climate is cool and humid, with mean annual precipitation of 107 cm evenly distributed throughout the year. Highest flows in all rivers occur in April as a result of spring runoff and snowmelt, and lowest flows occur in July through September (Flanagan et al. 1999). More than 1,600 dams in the area regulate flows in mid-sized to large rivers (basin areas > 250 km^2, Flanagan et al. 1999). Streams in this region support warmwater fish assemblages (Flanagan et al. 1999).

Birmingham (BIR).—The BIR study area is in

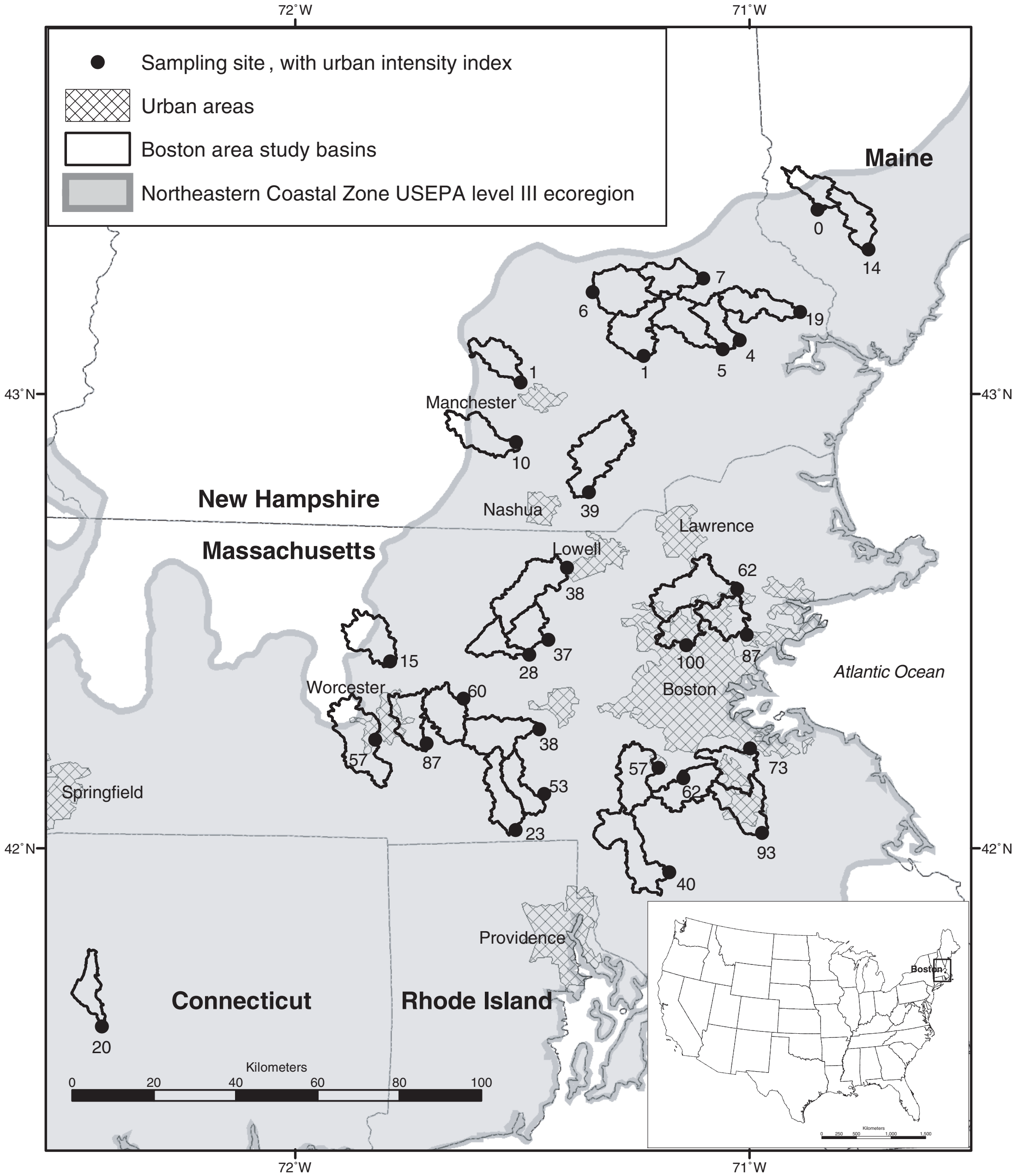

FIGURE 1. Location of study basins and sampling sites in relation to urban areas and U.S. Environmental Protection Agency (USEPA) level III ecoregions in the Boston, Massachusetts study area. Site numbers correspond to urban intensity index in Table 3.

Georgia and Alabama in the southeastern United States (Figure 2). Major metropolitan areas include Birmingham, Anniston, and Gadsden, Alabama, with 1990 populations of 839,942, 116,032, and 99,840, respectively (Johnson et al. 2002). The study area is in the Ridge and Valley ecoregion (Omernik 1987), where mountain ridges are typically sandstone, valley floors are primarily limestone or shale, and elevation ranges from about 183–488 m above sea level (Johnson et al. 2002). The dominant natural vegetative cover is Appalachian oak forest, and land use is predominantly cropland and pasture and urban lands (Johnson et al.

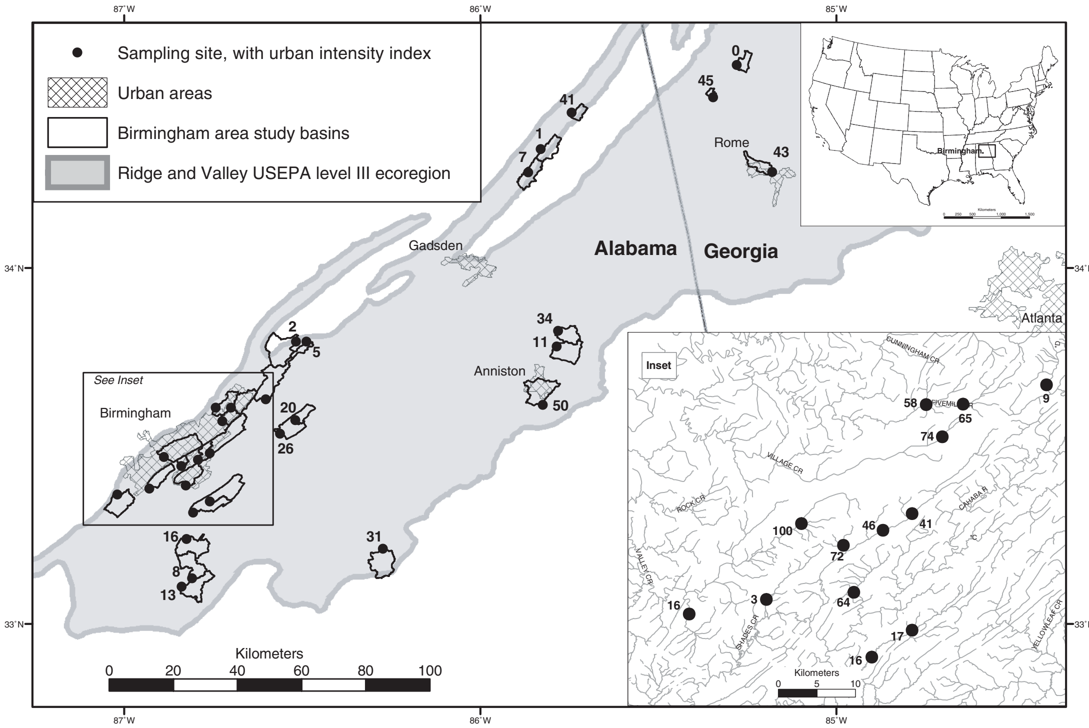

FIGURE 2. Location of study basins and sampling sites in relation to urban areas and U.S. Environmental Protection Agency (USEPA) level III ecoregions in the Birmingham, Alabama study area. Site numbers correspond to the urban intensity index in Table 3.

2002). The climate is warm and humid with mean annual rainfall of 139 cm, evenly distributed throughout the year, except for a dry period in August to October. Highest flows occur in February, and lowest flows occur in June to September (Johnson et al. 2002); however, flows during 1999–2001 were below the long-term (>50 years) average due to drought conditions in the region (Atkins et al. 2004). Streams in this region support warmwater fish assemblages.

Salt Lake City (SLC).—The SLC study area is located in north-central Utah in the western United States (Figure 3). The three largest cities in Utah, Salt Lake City, Provo, and Ogden, combined with their suburbs, have a total population of about 1.6 million people. These cities are along the western edge of the Wasatch Range, which rises from an elevation of about 1,280 m above sea level at the valley floor to more than 3,300 m (Baskin et al. 2002). The study area is in the Central Basin and Range ecoregion (Omernik 1994; Figure 3), which is characterized by xeric basins, scattered low and high mountains, and salt flats. Natural vegetation consists of sagebrush, saltbrush, and greasewood on dry alkaline soils, although vegetation in the urban areas is highly altered. Land use in the ecoregion is primarily irrigated agriculture and urban (Baskin et al. 2002). The climate of the study area is semiarid, with precipitation ranging from 30 to 41 cm on the valley floor to greater than 150 cm in the mountains. Summer months are typically dry, with precipitation occurring as thunderstorms (Baskin et al. 2002). Highest flows occur in May and June from snowmelt, and lowest flow from October to March in the Wasatch Range (Baskin et al. 2002). Streams in the study area arise in the Wasatch Range and flow westerly through the urban areas, where they support cool- and coldwater fish assemblages. Typical of arid and semiarid urban areas in the western United States, an array of reservoirs, diversions, and canals, alters the hydrologic regime of most SLC streams (Baskin et al. 2002).

Site Selection

We selected study basins through an iterative process of identifying candidate study basins. We used available Geographic Information System (GIS) data to group basins with similar natural characteristics (environmental setting). We then used additional GIS data to rank candidate basins by the UII, examined envi-

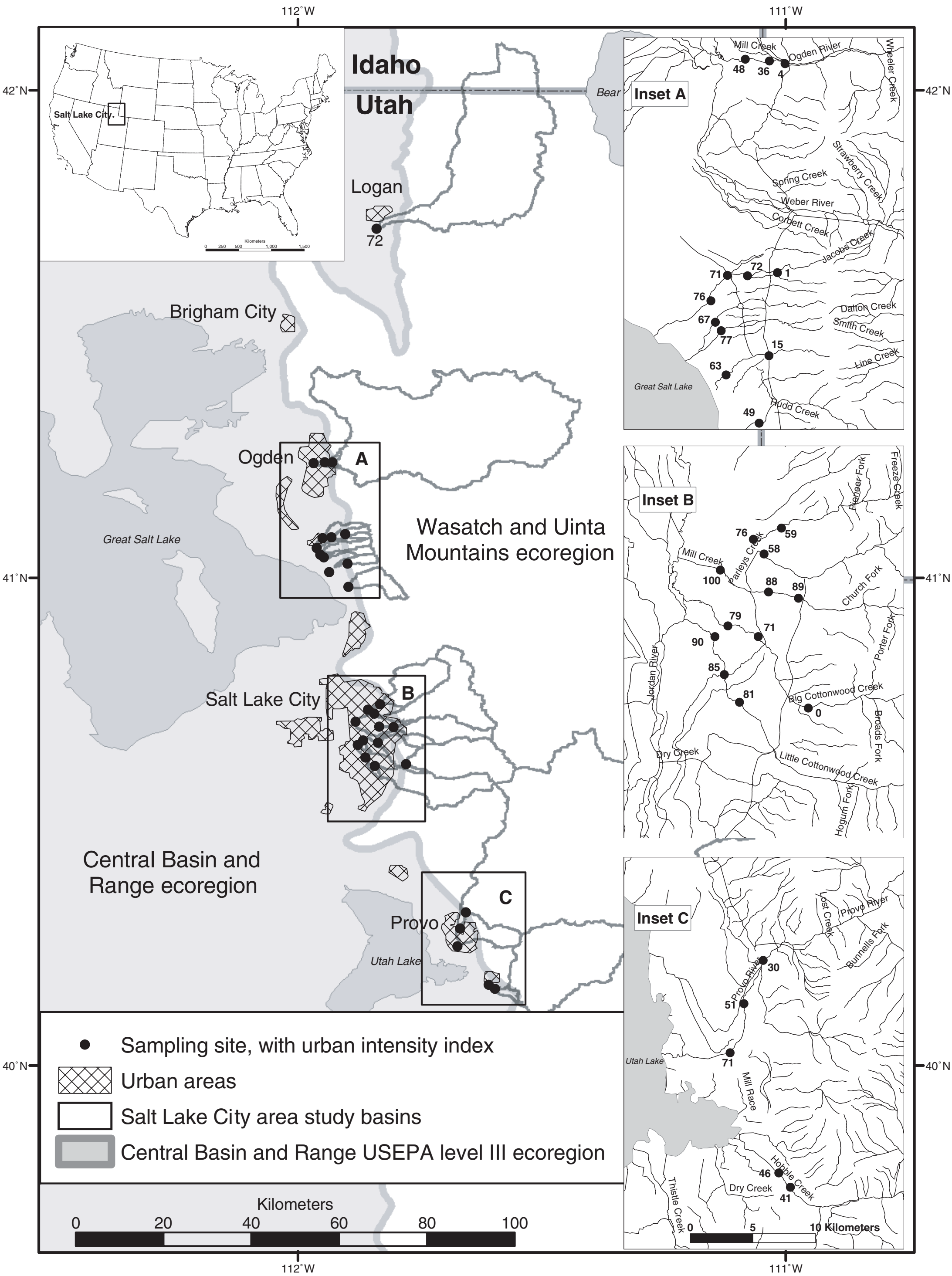

FIGURE 3. Location of study basins and sampling sites in relation to urban areas and U.S. Environmental Protection Agency (USEPA) level III ecoregions in the Salt Lake City, Utah study area. Site numbers correspond to the urban intensity index in Table 3.

ronmental setting groups, and selected a subset of candidate basins with similar natural characteristics that covers the range of UII. We visited candidate sites to validate GIS data and assessed site characteristics and access. Finally, we shifted site locations if necessary, refined basin boundaries, and repeated GIS analyses and UII calculations for the final set of sites.

Basin delineation.—A population of candidate basins in the BOS and BIR were delineated using 30-m digital elevation models (DEMs, U.S. Geological Survey 2000) and GIS programs to approximate 2nd–5th-order basins. We selected 206 candidate basins (50–250 km^2 in area) in the BOS study area and 375 candidate basins (5–130 km^2 in area) in the BIR study area. The process for SLC was different because the semiarid conditions of the SLC severely limited the number of streams that were available for study. To develop a population of candidate basins in SLC, we visited every stream in the Central Basin and Range ecoregion between Provo and Logan, Utah and assessed their suitability for inclusion in the urban gradient. To get the range of urban intensity values needed, we had to nest sites and use a larger range of basin sizes (4–1,764 km^2) than recommended by the original design. Once sites were selected, basin boundaries were delineated using 30-m DEMs and GIS programs.

Reducing natural variability.—To reduce natural variability for each study area, we grouped candidate basins on the basis of soil drainage characteristics (U.S. Department of Agriculture 1994), bedrock geology (lithology, BOS: Robinson 1997; SLC: Johnson and Raines 1995), topography, and ecoregions (Omernik 1987; Keys et al. 1995) (Table 1) to produce relatively homogeneous groups based on natural features in each study area.

The resulting groups (environmental setting) were consistent with U.S. Environmental Protection Agency (USEPA) level III ecoregion (Omernik 1987) or U.S. Forest Service (USFS) ecological units (Keys et al. 1995). Ecoregions provide a coarse framework of relatively homogenous climate, elevation, soils, geology, and vegetation and have been used to investigate regional water quality patterns (Hughes et al. 1994).

In BOS, we first located candidate basins in the USEPA level III Northeastern Coastal Zone ecoregion (Omernik 1987) that corresponds to the USFS Southern New England Coastal Hills and Plains ecological unit (Keys et al. 1995). To ensure a further degree of

TABLE 1. Sources of digital mapped information for calculating basin variables.

Basin characteristic	Maps	Scale	Reference
Watershed boundaries and topography	Developed from digital elevation models	100,000	U.S. Geological Survey 2000
Soils	U.S. Department of Agriculture State Soil Data Base (STATSGO)	250,000	U.S. Department of Agriculture 1994
Lithology	Bedrock lithology groups	~250,000	Johnson and Rains 1995; Robinson 1997
Ecological regions	U.S. Environmental Protection Agency (USEPA) level III ecoregions	7,000,000	Omernik 1987
	USEPA level IV ecoregions	1,700,000	Griffith et al. 2001
	U.S. Forest Service subsections (level IV)	3,500,000	Keys et al. 1995
Land-cover data	National land-cover data	100,000	Vogelman et al. 2001; U.S. Geological Survey 2002
Infrastructure	Roads (Census TIGER roads)	100,000	GeoLytics 1999
	Point source dischargers	Point	USEPA 1999
	USEPA Toxic Release Inventory	Point	USEPA 1997; Price and Clawges 1999
	Dams	Point	U.S. Army Corps of Engineers 1996
Census block group	Population, housing unit density, income, socio-economic indices	100,000	GeoLytics 1999

homogeneity among natural features, candidate basins were categorized using the 12 USFS ecological subsections that are analogous to higher resolution USEPA level IV ecoregions. This second categorization step provided a mechanism to reduce candidate basins down to a subset of basins having relatively little variability in their natural features. The Gulf of Maine Coastal Plain ecological subsection was selected as the primary area for the site network because it included basins that covered a range of urban intensity, including a significant portion of the urban, suburban, and rural areas in the BOS study area. Study basins were selected within 128 km of Boston. Low urban intensity basins are forested. One characteristic unique to BOS was the large number of small, historical millponds that substantially modify the natural hydrology. No streams were identified in central Boston either because they were not in the appropriate size range or were highly modified (e.g., concrete culvert).

In BIR, candidate basins were located in a geologically complex area of the southern Appalachians (USEPA level III Ridge and Valley ecoregion, Omernik 1987), where mountain ridges typically are composed of sandstone and the valley floors tend to be primarily limestone or shale. Candidate basins were then subdivided into relatively homogeneous groups based on four USEPA level IV subecoregions (Griffith et al. 2001) and through analysis of natural features data (e.g., geology, topography). The Southern Limestone/Dolomite Valleys and Low Rolling Hills subecoregion was selected as the primary area for the site network. We also restricted candidate basins to a single surficial geology type that included urban, suburban, and rural areas in the BIR study area. The Ridge and Valley topography lead to the sampling of multiple sites within the same basin. In this nested design, the downstream site integrated the inflows from many upstream tributaries. Sewer overflows and sedimentation from construction were two obvious local alterations in BIR; also, the 2000 sampling coincided with a severe drought that required dropping two sites that went dry during the study.

The SLC urban study focused on streams draining the western edge of the Wasatch Mountains (Figure 3). The mountainous terrain concentrates urban development at the lower end of the river basins in the USEPA level III Central Basin and Range ecoregion (Omernik 1994; Figure 3), but the upper portion of each basin and the source of most of the water are in the Wasatch and Uinta ecoregion. The ecoregion junction is an abrupt transition from an area with little or no urbanization to one with moderate to high urbanization. The SLC study area is heavily affected by water withdrawal, and some streams are piped beneath urban areas or confined by concrete channels. Large irrigation canals run along the edge of the Wasatch Mountains, and streams may receive irrigation overflows or return flows varying hourly and representing marked changes in water source, quantity, and quality. Because of the semiarid environment and numerous water diversions, only 13 perennial streams were suitable for study between Provo and Logan, Utah, requiring us to select one to three sites in each stream to meet the design goal of 30 sites covering the range of urban intensity. In addition, a much wider range in basin area (4–1764 km^2) was required, and one site lacked riffles. Sampling sites ranged in elevation from 1,250 m to 1,539 m because older and more intense urbanization was generally located near the valley floor and newer and less intense residential development was located closer to the mountains. In this nested design, downstream sites were used to represent increasing urban intensity even though they were not independent of conditions at upstream sites (Figure 3). Although we observed many low head dams and diversions, we located no quantification of their number or flows into or away from our study streams.

Urban intensity indices (UIIs).—Infrastructure, land-cover/land-use, and socioeconomic data were used as potential variables in our UIIs (Table 1). Infrastructure measures included road density, the number of point-source dischargers (USEPA 1999), the number of dams (U.S. Army Corp of Engineers 1996), and the number of Toxic Release Inventory sites (USEPA 1997; Price and Clawges 1999). Land-use/land-cover data came from National Land-Cover Data (NLCD; Vogelmann et al. 2001; U.S. Geological Survey 2002), which is based on Landsat Thematic Mapper satellite images from the early 1990s. Land use/land cover was characterized for the entire basin and for a 250-m buffer (125 m on either side of the stream channel) along all streams in the basin mapped at a 1:100,000 scale.

Census counts (1990) and estimates (1999) for population, labor, income, and housing variables, based on census block group areas, were used to characterize socioeconomic features of the urban landscape (GeoLytics 1999). Socioeconomic indices (SEI) were also derived for each basin using principal components analysis (PCA) of social, income, and housing variables (Anson 1991). Socioeconomic indices values were site scores along the PCA axes. Each axis represented a different combination of social, income, housing, and labor variables that characterize the major patterns of change across the urban gradient. We included these variables in the UII because socioeconomic conditions shape perceptions of degree (e.g., density) and character (e.g., affluence) of development within a drainage basin and may also affect factors that can influence water quality (Grove and Burch 1997; McMahon and Cuffney 2000). For example, population and housing density may provide a direct measure of development intensity that is likely correlated with impervious areas (Stankowski 1972). McMahon and Cuffney (2000) suggest that residential use of fertilizers and pesticides may vary according to the income levels of neighborhoods.

We developed separate UIIs for each study area in a consistent five-step process. First, all available GIS data for a study area that were associated with urbanization were normalized: areas into percent basin area, total counts to counts per 100 km^2, and socioeconomic index = SEI – minimum (SEI). Second, to focus on variables associated with population density (urban intensity), we only included variables that were at least moderately correlated ($|r| \geq 0.5$) with 1999 population density and not strongly correlated with basin area ($|r| < 0.5$). Third, we then range-standardized the remaining data so that values ranged from 0 to 100 (low to high): $Y = (X - X_{min}) \div (X_{max} - X_{min}) \times 100$, where X is the value of variable X for the site, Y is the transformed variable for the site, X_{min} is the minimum values of variable X over all sites, and X_{max} is the maximum values of X over all sites (McMahon and Cuffney 2000). Fourth, values for variables that were negatively correlated with population density were subtracted from 100 so all variables increased with increasing urban intensity. Fifth, we next averaged all of the range-standardized variables for each site and then range-standardized site values over all sites to produce a UII that ranged from 0 to 100 (McMahon and Cuffney 2000). This was the UII score for that site.

UII variables were selected on the basis of their correlation with population density because urbanization is characterized as the number of people using ecosystem resources and services in a defined space and time. We chose to use a multimetric UII and not population density as our sole indicator of urbanization for several reasons. Population density causes landscape changes that affect water quality, but it is not the direct cause of water quality degradation. Also, there are multiple causes of urban water quality degradation and we wanted to include multiple indicators to define urbanization. Variables that were highly correlated with each other were not omitted because by definition all variables included in the UII were correlated with changes in population density.

Reducing the number of sites.—We reduced the number of sites from 206 and 375 in BOS and BIR, respectively, to a more manageable number (<100) for site reconnaissance by examining sites within the different environmental setting groups in each study area. Environmental setting groups were based on sites with similar natural features (e.g., topography, geology, and soils) within an ecoregion. Sites in environmental setting groups were also examined to determine coverage along the urban gradient; that is, six sites distributed within five blocks along the length of gradient (i.e., 0–20, 20–40, 40–60, 60–80, 80–100) or as close an approximation as we could achieve. In this step, related environmental settings were combined to get the coverage of the urban gradient needed while maintaining as homogenous an environmental setting as possible. We then prioritized sites to include in the reconnaissance.

Reconnaissance.—Once the subset of candidate basins were identified, basins were visited to select 30 study sites in each study area, get site permissions, and assess physical access and local stream conditions such as land-use, point sources, riparian condition, and instream habitat characteristics. Criteria for selecting a sampling reach were that the stream reach was free-flowing for 150 m, had no signs of recent anthropogenic modification, had natural substrates, had riffle habitat, and had a well-defined bank with relatively complete (≥50%) vegetation cover. These criteria ensured that ecological differences within the sampling reach resulted from changes in the urban intensity in the basin rather than from differences within the reach (e.g., concrete lined channels).

Index recalculation and final site selection.—The reconnaissance visits caused shifts in the location of some sampling sites. This required redrawing basin boundaries and repeating the five-step process of scoring the UII for all 30 basins in a study area. The final sites represented the gradient in basin-scale urbanization with minimal differences in natural basin features (e.g., ecoregion, climate, topography, stream size) and local disturbances (e.g., major point sources, modifications to channels, bank, or bed).

Common urban intensity index (CUII) calculation.—Urban intensity indexes were developed individually for each study area to reflect the unique land-use, land-cover, infrastructure, population, and socioeconomic data available in each. These UIIs represent the range of urban intensity in each study area, but the variables comprising the index differed among study areas. Consequently, the level of urban intensity described by the UII may not be comparable among study areas. To address this issue, a CUII was also calculated based on a subset of five urban variables common to all three study areas: percentage of basin area in urban, percentage of basin area in forest + shrub land, percentage of stream network buffer in developed, percentage of stream network buffer in forest + shrub lands, and road density. The CUII provided a measure of urban intensity that was calculated in the same way as the UII, but was consistent among the study areas.

Data analyses.—Spearman rank correlations (r) were used to examine the strength of relations among population density or basin area and infrastructure, land-use, land-cover, socioeconomic, basin soil, and lithology variables. Spearman rank correlation was used to summarize the relations among variables because it was able to detect associations even when the underlying responses were not linear. Regression analysis (R^2) was used to examine population density as a predictor of UII, and UII as a predictor of land use, road density, and CUII. A significance level of 0.05 was used for regression analyses. Spearman rank correlations and regression analyses were performed using SYSTAT 9 (SPSS 1999). Principal components analysis used to derive socioeconomic indices was performed using SAS (SAS Inc. 1990).

Results

Natural Variability within Study Areas

In BOS, most basins were in the Gulf of Maine Coastal Plain ecological subsection with the exceptions of two basins that were located in the Southeast New England Coastal Hills and Plains and Worcester-Monadock Plateau ecological subsections (Table 2). Basin area, elevation, and slope varied relatively little among basins (Table 2) and stream sizes ranged from 3rd to 5th order (Table 3). Soil drainage characteristics and lithology, however, varied among basins (Table 2).

In BIR, most basins were in the Southern Limestone/Dolomite Valleys and Hills subecoregion with the exception of two basins that were located in the Southern Shale Valleys and the Southern Sandstone Ridges subecoregions. Basin size, elevations, slopes and soils varied relatively little among basins (Table 2) and stream sizes were mostly 2nd and 3rd order (Table 3).

In contrast to BOR and BIR, total basin area and elevation (Table 2), and stream sizes (2nd–6th order; Table 3) in SLC varied widely among basins. Basin area in the Central Basin and Range ecoregion portion

TABLE 2. Minimum (Min.), maximum (Max.), and median (Med.) of basin variables used to characterize the environmental setting and the urban intensity index for Boston (BOS), Birmingham (BIR), and Salt Lake City (SLC) studies. Variables for SLC are based on the Central Basin and Range ecoregion portion of the basin except for the range and mean elevation in the basin. See Table 1 for data sources.

	BOS			BIR			SLC		
Basin variables (units)	Min.	Max.	Med.	Min.	Max.	Med.	Min.	Max.	Med.
Environmental setting variables									
Basin area (km^2)	45.8	124.7	73.0	4.7	66.1	33.5	0.3	29.0	4.5
Topography									
Elevation (m)									
Sampling site	6	144	53	136	254	192	1,250	1,539	1,345
Range in basin	76	485	156	85	428	205	33	1,351	222
Mean in basin	31	237	105	163	324	241	1,376	2,355	1,467
Basin slope (% of basin area)									
Slope < 1%	2	31	11	1	29	3	0	12	2
Slope < 1%, > midpoint elevation (uplands)	0	6	1	0	7	0	0	1	0
Slope < 1%, • midpoint elevation in the basin (lowlands)	1	29	10	0	29	3	0	12	2
Soils									
Hydrologic soil groups (% of basin area)									
A, minimum infiltration rate 8–12 mm/h	0	74	19	–	–	–	0	7	0

TABLE 2. Continued.

Basin variables (units)	BOS			BIR			SLC		
	Min.	Max.	Med.	Min.	Max.	Med.	Min.	Max.	Med.
B, minimum infiltration rate 4–8 mm/h	0	92	0	6	100	86	0	100	90
C, minimum infiltration rate 1–4 mm/h	0	88	0	0	94	0	0	100	0
D, minimum infiltration rate 0–1 mm/h	0	55	1	0	65	0	0	95	0
Soil drainage (% of basin area)									
Well-drained soils	5	98	45	6	100	86	0	100	90
Poorly drained soils	2	95	54	0	94	14	0	00	9
Average soil volume proportion of sand	19	45	34	4	18	14	7	38	25
Lithology (% of basin area)									
Quartzite	–	–	–	–	–	–	0	31	0
Alluvium	–	–	–	–	–	–	0	84	12
Lake sediment and playa	–	–	–	–	–	–	0	94	56
Granitic gneiss	–	–	–	–	–	–	0	100	0
Carbonate rich	0	90	0	–	–	–	–	–	–
Carbonate poor, cliastic sedimentary, depositonal basins	0	74	0	–	–	–	–	–	–
Mafic igneous and metamorphic equivalents	0	64	3	–	–	–	–	–	–
Ultramafic	0	87	1	–	–	–	–	–	–
Metamorphosed clastic sedimentary	0	97	47	–	–	–	–	–	–
Felsic igneous and plutonic	0	94	0	–	–	–	–	–	–
Ecoregions (% of basin area)									
U.S. Forest Service ecological units									
Southern New England Coastal Hills and Plains									
Boston Basin	0	68	0	–	–	–	–	–	–
Narragansett/Bristol Lowlands	0	61	0	–	–	–	–	–	–
Southeast New England Coastal Hills and Plains	0	100	0	–	–	–	–	–	–
Worcester/Monadnock Plateau	0	100	0	–	–	–	–	–	–
Gulf of Maine Coastal Plain	0	100	99	–	–	–	–	–	–
U.S. Envrionmental Protection Agency ecoregions									
Ridge and Valley									
Southern Limestone/ Dolomite Valleys	–	–	–	0	100	72	–	–	–
Southern Shale Valleys	–	–	–	0	98	0	–	–	–
Southern Sandstone Ridges	–	–	–	0	100	0	–	–	–
Plateau Escarpment	–	–	–	0	35	0	–	–	–
Southern Table Plateaus	–	–	–	0	43	0	–	–	–
Central Basin and Range	–	–	–	–	–	–	100	100	100

TABLE 2. Continued.

Basin variables (units)	BOS Min.	BOS Max.	BOS Med.	BIR Min.	BIR Max.	BIR Med.	SLC Min.	SLC Max.	SLC Med.
Urban intensity index variables									
Land use/land cover (National Land-Cover Data)									
Basin level (% of basin area)									
Developed	2	67	15	0	73	11	0	87	40
Low intensity residential	1	50	10	0	34	7	0	77	30
High intensity residential	0	4	0	0	17	1	0	0	0
Commercial/industrial/ transportation	0	14	3	0	23	3	0	19	4
Forest	23	86	65	18	93	64	2	47	11
Deciduous	14	60	28	9	55	27	0	16	5
Evergreen	1	32	5	1	26	12	1	31	3
Mixed	7	42	18	6	33	24	0	12	1
Shrubland	0	0	0	–	–	–	1	68	12
Deciduous	–	–	–	–	–	–	0	67	8
Herbaceous planted/cultivated									
Pasture/hay	0	6	1	0	26	7	0	38	6
Row crops	0	9	4	0	8	3	0	0	0
Urban/recreational grasses	0	10	2	0	11	3	0	25	8
Stream buffers (250 m, % of buffer area)									
Developed	2	60	12	0	68	16	0	78	32
Forest	25	82	60	22	89	62	4	57	14
Shrubs	–	–	–	–	–	–	3	58	14
Infrastructure									
Road density in basin (km/km^2)	1	9	3	5	50	15	0	45	20
Point source discharger density (number/100 km^2)	0	15	0	–	–	–	–	–	–
USEPA Toxic Release Inventory density (number/100 km^2)	0	40	3	–	–	–	–	–	–
Dam density (number/100 km^2)	0	18	6	–	–	–	–	–	–
Socioeconomic indices (SEI) variables									
SEI2	–3.6	1.5	–0.6	–3.7	3.7	–0.9	–4.4	3.3	0.4
SEI3	–1.3	2.8	1.2	–	–	–	–	–	–
SEI5	–0.7	1.8	1.0	–	–	–	–	–	–
Population and housing variables									
1999 population density (people/km^2)	25	1,261	205	10	1,543	214	13	2,251	813
Change in population density 1990 to 1999 (people/km^2)	–2	82	12	–47	129	6	1	278	166
Percent of families with female head of household	5	19	8	–	–	–	–	–	–
Percent of minorities in 1999	0	10	2	–	–	–	–	–	–
Percent occupied housing units that are renter occupied, 1990	5	28	16	–	–	–	–	–	–
Percent of 1990 housing units built before 1980	58	88	71	–	–	–	–	–	–
Percent of housing units on public	–	–	–	3	97	42	1	100	94

TABLE 3. Urban intensity index (UII), common urban intensity index (CUII), and selected characteristics for study basins. UII values correspond to sampling site locations in each basin in Figures 1, 2, and 3.

Site name	Urban intensity index (UII)	Common urban intensity index (CUII)	1999 population density (number/ km^2)	Total basin area (km^2)	Basin area in Central Basin and Range eco-region (km^2)	Stream order
Boston, Massachusetts						
Little River near Lebanon, ME	0	1	41	45.8	–	4
Black Brook Dunbarton Road near Manchester, NH	1	5	55	53.7	–	4
Lamprey River Cotton Road near Deerfield, NH	1	4	27	83.1	–	4
Little River at Cartland Road at Lee, NH	4	7	39	52.2	–	3
North River at Route 152 near Nottingham, NH	5	6	31	74.9	–	5
Little Suncook River Blackhall Road at Epsom, NY	6	11	34	101.4	–	4
Isinglass River Batchelder Road near center Strafford, NH	7	8	25	59.4	–	3
Baboosic River Bedford Road near Merrimack, NH	10	11	123	73.0	–	4
Greatworks River near North Berwick, ME	14	11	95	60.2	–	4
Stillwater River near Sterling,	15	9	60	78.7	–	3
Bellamy River at Bellamy Road near Dover, NH	19	14	87	68.5	–	4
Blackledge River above Lyman Brook near North Westchester, CT	20	12	94	49.2	–	3
Mill River at Summer Street near Blackstone, MA	23	15	204	73.7	–	5
Elizabeth Brook off White Pond Road near Stow, MA	28	14	91	48.5	–	4
Fort Pond Brook at River Road near South Acton, MA	37	19	228	53.7	–	4
Stony Brook at North Pelham, NH	38	27	193	107.7	–	4
Sudbury River at Concord Street at Ashland, MA	38	22	212	89.6	–	5
Beaver Brook at North Pelham, NH	39	38	349	121.7	–	4
Wading River (head of Threemile River) near Norton, MA	40	23	208	113.4	–	4
Charles River at Maple Street at North Bellingham, MA	53	32	529	54.2	–	4
Middle River off Sutton Lane at Worcester, MA	57	34	499	124.7	–	5
Neponset River at Norwood, MA	57	36	477	84.9	–	5

TABLE 3. Continued.

Site name	Urban intensity index (UII)	Common urban intensity index (CUII)	1999 population density (number/km^2)	Total basin area (km^2)	Basin area in Central Basin and Range eco-region (km^2)	Stream order
Assabet River at Allen Street at Northborough, MA	60	34	295	76.4	–	5
East Branch Neponset River at Canton, MA	62	43	605	72.9	–	5
Ipswich River at South Middleton, MA	63	47	445	115.3	–	4
Monatiquot River at River Street at Braintree, MA	73	50	808	71.2	–	4
Quinsigamond River at North Grafton, MA	87	52	781	66.2	–	4
Saugus River at Saugus Ironworks at Saugus, MA	87	63	1,015	60.4	–	4
Matfield River at North Central Street at East Bridgewater, MA	93	56	1,261	79.8	–	4
Aberjona River (head of Mystic River) at Winchester, MA	100	75	1,204	58.2	–	5
Birmingham, Alabama						
Chappel Creek at Long Branch Road near Trion, GA	0	6	35	14.3	–	2
Mush Creek near Portersville, AL	1	5	10	24.5	–	3
Big Canoe Creek at Canoe Creek Road near Springville, AL	2	2	55	54.3	–	4
Little Shades Creek at State Highway 150 near Bessemer, AL	3	0	46	21.7	–	2
Unnamed Tributary to Big Canoe Creek near Springville, AL	5	8	45	10.5	–	2
Little Wills Creek at Collins Chapel Road at Collinsville, AL	7	10	14	27.9	–	3
Spring Creek at County Road 16 near Moores Crossroads, AL	8	16	102	33.1	–	3
Cahaba River above Trussville, AL	9	–	94	50.1	–	–
Little Tallaseehatchee Creek near Weaver, AL	11	5	66	38.1	–	3
Dry Creek at Spring Creek Road near Montevallo, AL	13	15	74	34.7	–	2
Five Mile Creek at Nevel Road near McCalla, AL	16	22	96	33.9	–	2

TABLE 3. Continued.

Site name	Urban intensity index (UII)	Common urban intensity index (CUII)	1999 population density (number/km^2)	Total basin area (km^2)	Basin area in Central Basin and Range eco-region (km^2)	Stream order
Cahaba Valley Creek at Cross Creek Road at Pelham, AL	16	15	50	66.0	–	3
Buck Creek at Buck Creek Road at Alabaster, AL	16	16	224	38.7	–	3
Cahaba Valley Creek at Indian Trail Road near Indian Springs, AL	17	15	40	36.9	–	3
Little Cahaba River near Braggsville, AL	20	32	420	15.7	–	2
Little Cahaba River below Leeds, AL	26	31	205	43.9	–	2
Shirtee Creek near Odena, AL	31	32	189	43.3	–	3
Williams Branch near Jacksonville, AL	34	29	303	23.9	–	2
Unnamed Tributary to Big Wills Creek at State Route 35 near Fort Payne, AL	41	44	358	12.1	–	2
Shades Creek at Lakeshore Drive near Mountain Brook, AL	41	36	498	42.1	–	2
Little Dry Creek at US 27 at Rome, GA	43	–	295	20.0	–	–
Town Branch near Summerville, GA	45	44	351	4.7	–	2
Shades Creek at Samford University at Homewood, AL	46	40	536	56.3	–	3
Snow Creek below Anniston, AL	50	51	426	44.7	–	2
Fivemile Creek at Lawson Road near Tarrant City, AL	58	52	768	48.6	–	3
Patton Creek near Bluff Park below Patton Chapel, AL	64	61	824	28.8	–	2
Fivemile Creek at Fivemile Road near Huffman, AL	65	58	857	25.0	–	3
Unnamed Tributary to Shades Creek near Oxmoor, AL	72	68	560	6.0	–	2
Village Creek at East Lake in Birmingham, AL	74	72	826	14.2	–	2
Valley Creek at Cleburn Avenue at Powderly, AL	100	100	1,543	52.1	–	3
Salt Lake City, Utah						
Big Cottonwood Creek above Water Treatment Plant at Salt Lake City, UT	0	15	13	128.7	0.3	3

TABLE 3. Continued.

Site name	Urban intensity index (UII)	Common urban intensity index (CUII)	1999 population density (number/km^2)	Total basin area (km^2)	Basin area in Central Basin and Range eco-region (km^2)	Stream order
South Fork Kays Creek at Fernwood Picnic Area at Layton, UT	1	10	53	3.9	3.9	2
Ogden River at Valley Drive Ogden, UT	4	29	23	855.2	0.8	6
Baer Creek at 1800 East at Fruit Heights, UT	15	21	45	9.3	0.3	2
Provo River at Highway 189 at Provo, UT	31	29	212	1,709.9	3.6	5
Ogden River at Harrison Avenue at Ogden, UT	36	43	635	857.5	3.1	6
Hobble Creek at 800 East at Springville, UT	41	37	270	319.1	9.6	5
Hobble Creek at Center Street at Springville, UT	46	42	389	320.1	10.6	5
Ogden River at Washington Avenue at Ogden, UT	48	52	862	858.8	4.4	6
Farmington Creek at Frontage Road at Farmington, UT	49	42	443	32.6	3.1	3
Provo River at 3700 North	51	42	765	1,714.1	7.8	5
Parleys Creek at Sugarhouse Park at Salt Lake City, UT	58	55	839	139.9	4.7	4
Emigration Creek at 1300 South at Salt Lake City, UT	59	60	635	72.5	3.1	3
Baer Creek at Frontage Road at Kaysville, UT	63	54	748	12.7	3.6	2
North Fork of Holmes Creek at Main Street at Layton, UT	67	53	611	14.2	7.0	2
Kays Creek at 1000 East at Layton, UT	71	55	786	23.8	10.1	3
Provo River at 800 North at Salt Lake City, UT	71	37	1,515	1,764.0	24.1	5
Big Cottonwood Creek at Cottonwood Mall at Salt Lake City, UT	71	65	1,178	160.3	14.5	3
Logan River at Golf Course Road at Salt Lake City, UT	72	77	993	562.3	4.7	5
South Fork of Kays Creek at Layton, UT	72	61	596	12.9	3.1	3
Kays Creek at Layton, UT	76	59	1,033	28.0	3.1	3
Emigration Creek at 1200 East at Salt Lake City, UT	76	75	1,334	73.6	4.1	3
Holmes Creek at Main Street at Layton, UT	77	64	1,165	8.8	2.3	3
Big Cottonwood Creek at 900 East at Salt Lake City, UT	79	63	1,436	184.1	26.7	3

TABLE 3. Continued.

Site name	Urban intensity index (UII)	Common urban intensity index (CUII)	1999 population density (number/km^2)	Total basin area (km^2)	Basin area in Central Basin and Range eco-region (km^2)	Stream order
Little Cottonwood Creek at Crestwood Park at Salt Lake City, UT	81	75	1,553	93.8	9.8	3
Little Cottonwood Creek at Wheeler Farm at Salt Lake City, UT	85	76	1,724	97.6	13.7	3
Mill Creek at 2000 East at Salt Lake City, UT	88	79	1,749	60.1	2.1	4
Mill Creek at 3060 East at Salt Lake City, UT	89	80	1,700	59.6	1.6	4
Little Cottonwood Creek at Murray Park at Salt Lake	90	83	1,906	112.9	29.0	3
Mill Creek at 300 East at Salt	100	96	2,251	84.7	25.1	4

of the SLC basin also varied (0.3–29 km^2; Table 2). In the SLC, only data from the portions of the basins in the Central Basin and Range ecoregion (Tables 2 and 3) was used to calculate scores for the UII and CUII. This was done because the upper extent of urbanization approximates the junction between the Wasatch and Uinta Mountain ecoregion and the Central Basin and Range ecoregion, leading to an abrupt transition from an area with little or no urbanization to one with moderate to high levels of urbanization (Figure 3). The Wasatch and Uinta Mountain ecoregion was such a large proportion of total basin area that it diluted the measures of urban intensity. In addition, Wasatch and Uinta Mountain waters were variably diverted among basins, confounding their contributions to downstream sampling sites. The site visits and recalculations of basin characteristics for the Central Basin and Range ecoregion also aided in narrowing the natural variability among sites.

Comparison of Components of UIIs among Study Areas

The UII component variables were selected on the basis of correlation with population density (Table 4). Variables included in the final UII varied (23 for BOS, 15 for BIR, 13 for SLC), but each study area included land-use/land-cover, infrastructure, and socioeconomic variables. In all study areas, the amount of developed land (basin level or stream buffer), road density, and SEI2 increased whereas the amount of natural land cover (forest or shrubs) in the basin or stream buffers decreased with increasing population density (Table 4). Differences in variables included in the UII were related to local data availability and natural differences among study areas. In contrast to BOS and BIR, the limited number of streams, nested design, and water management features in SLC made reducing the number of sites on the basis of using the homogeneous environmental setting impracticable, and therefore basin soils and lithology variables were included in the calculation of the UII. Water diversions and dams were common in SLC; however, the information needed to quantify these water management features were not available so they were not included in the UII. The BOS included dam density in the UII because it is an important landscape feature as urban intensity increased within the area. In contrast, no measure of dams or other water management features were included in the UII for BIR.

Each study area had at least one socioeconomic index included in the UII, and BOS had three (Tables 4 and 5). Eigenvalues for the PCA axes ranged from 2.63 to 10.42 (Table 5), and the percent of variance explained among block groups ranged from 4.8 to 18.9. In all study areas, the SEI2 had high loadings for variables that represented increasing population and housing density.

TABLE 4. Spearman rank correlation coefficients for variables correlated with 1999 population density for the Boston (BOS), Birmingham (BIR), and Salt Lake City (SLC) study areas. Variables with correlation coefficients in bold were included in the urban intensity index. *, variable was included in common urban intensity index; –, variable not used.

	Correlation coefficients		
Variables	BOS	BIR	SLC
Land-use/land-cover variables			
Basin level (% of basin area)			
*Developed	**0.965**	**0.891**	**0.960**
Low intensity residential	**0.963**	**0.845**	–
High intensity residential	**0.888**	**0.852**	–
Commercial/industrial/transportation	**0.872**	**0.789**	–
*Forest	**–0.939**	**–0.868**	**–0.577**
Deciduous forest	–0.229	**–0.678**	–
Evergreen forest	**–0.717**	–0.451	–
Mixed forest	**–0.767**	**–0.574**	–
*Shrub	0.247	–	**–0.693**
Deciduous shrubland	0.247	**–0.685**	–
Herbaceous planted/cultivated			
Pasture/hay	–0.411	**–0.685**	–
Row crops	**–0.680**	–0.346	–
Urban/recreational grasses	**0.695**	**0.796**	–
Stream buffers (% of buffer area)			
*Developed	**0.942**	**0.877**	**0.957**
*Forest	**–0.865**	**–0.788**	**–0.595**
*Shrub	–	–	**–0.816**
Infrastructure variables			
*Road density in basin (km/km^2)	**0.964**	**0.908**	**0.759**
Toxic release inventory site density (number/100 km^2)	**0.858**	–	–
Point source discharger density (number/100 km^2)	**0.613**	–	–
Dam density (number/100 km^2)	**0.621**	–	–
Socioeconomic variables			
Socioeconomic index 2	**0.707**	**0.789**	**0.848**
Socioeconomic index 3	**–0.878**	–0.121	0.168
Socioeconomic index 5	**–0.712**	–0.482	0.264
Population and housing variables			
Change in population density from 1990 to 1999	**0.927**	–0.179	**0.893**
Percent of families with female head of household	**0.772**	–	–
Percent of 1999 population of minorities	**0.811**	–	–
Percent occupied housing units that are renter occupied, 1990	**0.690**	–	–
Percent of 1990 housing units built before 1980	**0.751**	–	–
Percent of housing units on public sewer, 1990	–	**0.763**	**0.626**
Basin soil and lithology variables (% of basin area)			
Soil group B, minimum infiltration rate 8–12 mm/h	–	–	**0.559**
Well-drained soils	–	–	**0.630**
Lake sediment and playa	–	–	**0.606**

Comparison of UIIs with Population Density and Other Variables

The UII was related to 1999 population density for each study area (BOS: $Y = 0.080X + 11.1$, $R^2 = 0.88$; BIR: $Y = 0.069X + 7.8$, $R^2 = 0.88$; SLC: $Y = 0.040X + 22.6$, $R^2 = 0.80$; Y = UII, X = 1999 population density). This was expected because component variables were selected based on correlation with population density. There was not, however, a 1:1 relation (slope ≠ 1) between UII and 1999 population density (Figure 4). The rate of change in urban intensity as mea-

TABLE 5. Variables included in the socioeconomic indices (SEIs) for the Boston (BOS), Birmingham (BIR), and Salt Lake City (SLC) study areas. The SEIs were derived from principal component analyses (PCA) of Census block group variables for each drainage basin. Variables with relatively high (≥0.2) or low (≤–0.2) loadings on each axis are in bold.

	BOS			BIR	SLC
Variable	SEI2	SEI3	SEI5	SEI2	SEI2
PCA	axis 2	axis 3	axis 5	axis 2	axis 2
Eigenvalue	8.54	5.24	2.63	9.64	10.42
Percent variance explained by PCA axis (%)	15.4	9.5	4.8	17.6	18.9
Socioeconomic variables					
1990 population density (people/km^2)	**0.323**	–0.138	0.020	**0.248**	**0.264**
1999 population density (people/km^2)	**0.315**	–0.155	0.000	**0.252**	**0.257**
Percent of population 65 or older, 1990	–0.003	0.039	**0.387**	–0.004	0.087
Number of families/ km^2, 1990	**0.319**	–0.153	0.020	**0.253**	**0.269**
Percent of total population with rural residence, 1990	–0.164	**–0.323**	0.112	**–0.249**	**–0.244**
Percent of total population with urban residence, 1990	0.164	**0.323**	–0.112	0.249	0.224
Households/ km^2, 1990	**0.316**	–0.162	0.028	**0.252**	**0.262**
Households/ km^2, 1999	**0.311**	–0.177	0.014	**0.255**	**0.263**
Number of housing units/ km^2, 1990	**0.315**	–0.163	0.027	**0.245**	**0.255**
Percent occupied housing units that are renter occupied, 1990	0.130	**0.221**	–0.056	0.133	0.107
Percent of housing units on public sewers, 1990	0.169	**0.333**	0.088	**0.238**	**0.208**
Percent of housing units using septic systems, 1990	–0.168	**–0.332**	0.085	**–0.233**	**–0.203**
No vehicles available to household, 1990	0.082	0.142	**0.284**	0.055	0.101
One vehicle available to household, 1990	0.068	0.111	**0.261**	0.077	0.159
Two vehicles available to household, 1990	0.003	0.023	**0.310**	0.036	0.110
Three vehicles available to household, 1990	–0.051	–0.066	**0.320**	–0.019	0.034
Per capita income/km^2, 1999	**0.279**	**–0.202**	–0.002	0.151	**0.220**
Drug expenditures per household, 1999	–0.014	–0.060	**–0.200**	–0.032	0.002
Proportional change in per capita income between 1990 and 1999	0.006	0.046	**0.270**	0.051	0.087

sured by the UII was greater at low (<500 people/km^2) compared to high (>500 people/km^2) 1999 population densities for all study areas (Figure 4). The 1999 population density ranged from 10 to 102 people/km^2 at low urban intensities (UIIs < 10) and was similar for all study areas (Table 3). In contrast, SLC had the highest population density at a UII of 100 compared to BOS and BIR (Table 3; Figure 4).

Infrastructure and socioeconomic (SEI2, population, and housing) variables increased with increasing UII (Table 4). Developed land (BOS: $Y = 0.60X - 2.41$, $R^2 = 0.92$; BIR: $Y = 0.70X - 3.52$, $R^2 = 0.98$; SLC: $Y = 0.84X - 9.59$, $R^2 = 0.83$; Y = developed land, X = UII) and road density ($Y = 0.07 + 0.96$, $R^2 = 0.94$; BIR: $Y = 0.41X + 5.11$, $R^2 = 0.93$; $Y = 0.26X + 4.78$, $R^2 = 0.41$; Y = road density, X = UII) increased whereas natural vegetation (forest in BOS: $Y = 0.56X + 82.2$, $R^2 = 0.95$; forest in BIR: $Y = 0.57X + 82.7$, $R^2 = 0.83$; forest + shrub in SLC: $Y = 0.62X + 63.4$, $R^2 = 0.60$; Y = forest + shrub, X = UII) decreased as UII increased in all study areas (Figure 5). The rate of change for some variables in relation to the UII, however, differed among study areas and demonstrates differences in patterns of urbanization among study areas. For example, the range in road density in BOS (1–9 km/km^2) was much narrower compared to BIR (5–50 km/km^2) and SLC (0–45 km/km^2; Table 2; Figure 5). Further, the strength of the relation (R^2) of developed land, road density, and forest + shrub versus the UII for SLC than BOS and BIR (Figure 5).

Comparing UII to CUII among Urban Areas

The CUII was strongly related to the UII for each study area (BOS: $Y = 1.52X - 1.90$ $R^2 = 0.98$; BIR: $Y = 1.06X - 1.93$ $R^2 = 0.97$; SLC: $Y = 1.19X - 5.69$ $R^2 = 0.86$; Y = UII, X = CUII; Figure 6). Intercepts were all relatively close to zero indicating correspondence at low levels of urban intensity. There was almost a 1:1 relation between CUII and UII in BIR and SLC, but not in BOS where a unit of CUII corresponds to 1.52 units of UII. Consequently, the rate of change in ur-

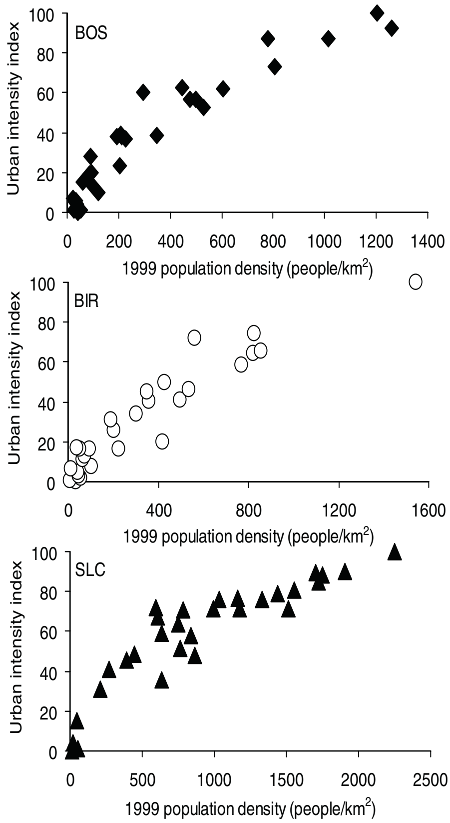

FIGURE 4. Relation of urban intensity index to 1999 population density for the Boston (BOS), Birmingham (BIR), and Salt Lake City (SLC) study areas.

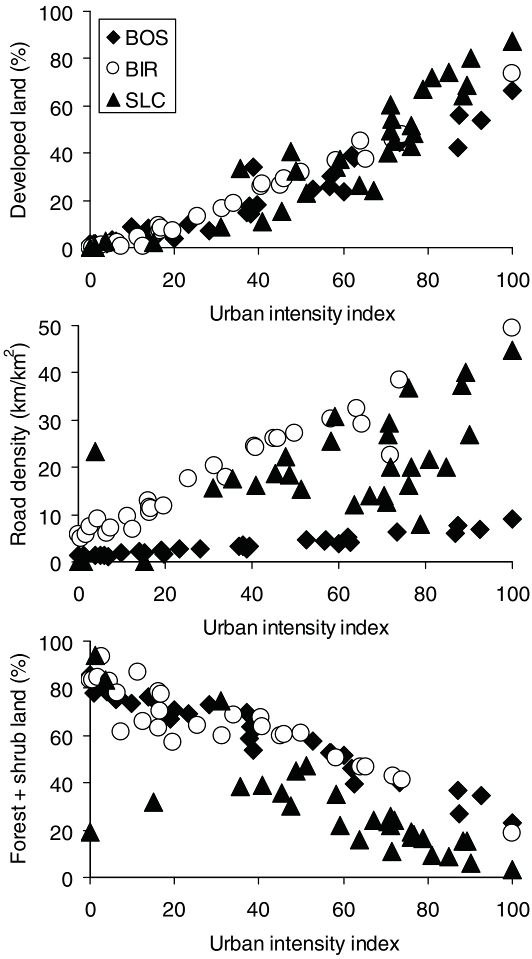

FIGURE 5. Relations of developed land use, road density, and forest + shrub land use with the urban intensity index for the Boston (BOS), Birmingham (BIR), and Salt Lake City (SLC) study.

ban intensity in BOS is higher when expressed as CUII than as UII. In addition, maximum levels of urban intensity (Table 3), as measured by CUII and UII, were different in BOS (CUII = 75; UII = 100) but not in BIR (CUII = 100, UII = 100) or SLC (CUII = 96, UII = 100). This is important when comparing the rate of response of aquatic assemblage, water chemistry, or physical habitat to urban intensity among study areas. Response rates that are similar for all study areas based on the UII will be greater in BOS compared to BIR or SLC when using the CUII.

The cumulative distribution of sites across the urban gradients expressed either as UII (Figure 7A) or CUII (Figure 7B) showed that BOS and BIR were similar, but SLC was different. The SLC had a higher proportion of sites (57% for UII, 43% for CUII) located at the high end (UII or CUII > 60 units) and a lower proportion (20% for UII and CUII) at the low end (UII or CUII < 40 units) of the urban gradient. In contrast, BOS and BIR had 60% of sites for UII and 76% (BOS) and 64% (BIR) of sites for CUII at the low end (UII or CUII < 40) and few sites (4 and 1 sites using UII; 0 and 1 site using CUII, for BOS and BIR, respectively) at the high end (UII or CUII > 80 units) of the gradient. Thus, we did not find sites that were evenly distributed along an urban intensity gradient within each study area despite our efforts.

Discussion

For several reasons, we used a multimetric UII that was based on basin variables that correlated with population density rather than rely solely on population density as our indicator of urbanization. Population density causes landscape changes that affect water

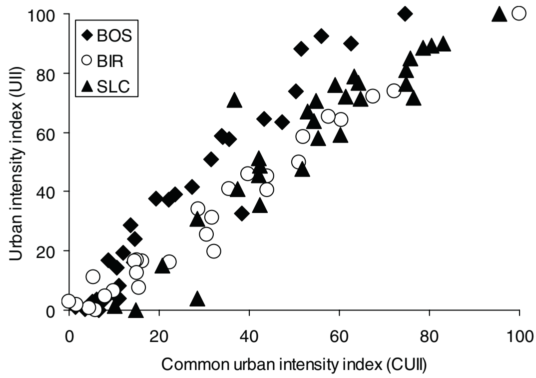

FIGURE 6. Relation of the common urban intensity index (CUII) derived from land use and infrastructure variables common to all three urban studies to the urban intensity index (UII) derived from study-specific land use, infrastructure, and socioeconomic variables for the Boston (BOS), Birmingham (BIR), and Salt Lake City (SLC) study areas.

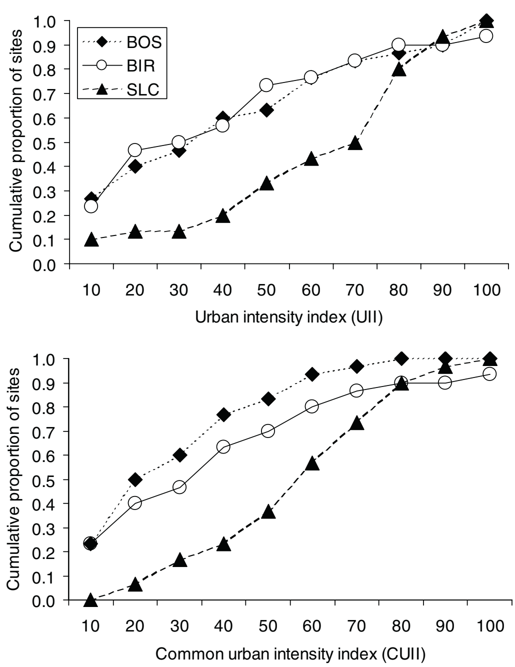

FIGURE 7. Cumulative distribution of sampling sites across the study-specific urban intensity index (UII) and the common urban intensity index (CUII) for the Boston (BOS), Birmingham (BIR), and Salt Lake City (SLC) study areas.

quality (aquatic assemblages, physical habitat, water chemistry), but it is not the direct cause of stream-quality degradation. We also wanted to provide managers with insight into what variables associated with urbanization were most strongly associated with water quality changes and could be manipulated to improve water quality. Finally, there are multiple causes of urban water quality degradation, and we wanted to include multiple indicators to define urbanization. The UII provides a mechanism of summarizing a variety of variables that are associated with changes in population density that is similar to deriving an index of biotic integrity (IBI) to describe biological conditions, where limited redundancy is acceptable.

Variables included in UII were correlated with population density, however, the UII did not show a 1:1 association with population density (Figure 4). In all study areas, the UII was a more sensitive indicator of urban intensity than population density at low levels of urbanization (Figure 4), where changes in water quality due to urbanization have been reported to occur (e.g., Paul and Meyer 2001 and reference within).

Comparison of variables included in the UII demonstrated similarities and differences in patterns of urbanization among the study areas (Tables 2 and 4; Figures 4 and 5). For example, the pattern of increased developed land and decreased natural vegetation with increasing UII was relatively similar among study areas (Figure 5). The range and rate of increase in road density with increasing UII, however, varied greatly among study areas with BIR > SLC > BOS (Table 2; Figure 5). Population density was greater at the high end of the UII in SLC compared to BOS and BIR (Figure 4). In addition, the BOS UII included point source discharger density, dam density, and more socioeconomic variables than BIR and SLC UIIs whereas the SLC UII included soil and lithology variables not included in BOS and BIR UIIs (Tables 2 and 4).

The UII provides a measure of urban intensity that maximizes use of locally available information, but is not directly comparable among study areas. The CUII provides a measure of urban intensity that is directly comparable among study areas. The UII and CUII were strongly related to one another because the CUII was based on a subset of the UII variables (Figure 6). The strong relation between the CUII and UII within each study basin dictates that correlations between response variables (e.g., aquatic assemblages, physical habitat, water chemistry) will be similar whether urban intensity is characterized by the CUII or UII. The rate of response between these water quality variables and increasing urban intensity, however, would be greater in BOS compared to BIR or SLC, when using the CUII, because the response would occur over a smaller range of urban intensity (Figure 6).

The application of the urban land-use gradient design of McMahon and Cuffney (2000) differed among the three study areas because of regional differences in the environmental setting and patterns of urbanization. The use of the UII to define an urban intensity gradient within a homogenous environmental setting within a study area worked relatively well in the humid eastern part of the United States (BOS and BIR), although BIR had some nested basins due to topography and both had a limited number of sites at the high end of the urban scale (Figure 7). In contrast, the semiarid climate of the Central Basin and Range ecoregion and the abrupt transition with the Wasatch-Uintah ecoregion limited the number of SLC basins from which to choose. Fewer basins contributed to a number of study design differences, including nested sites, greater variability in basin size, the inability to use homogeneous environmental settings, and the lack of sites on the low end of the urban scale. In all studies, however, the UII and CUII were calculated using the same procedure, sites were distributed across a range of urban intensity, and differences in local site characteristics (e.g., instream habitat and anthropogenic alterations) were minimized so that aquatic assemblage responses to increasing urban intensity could be compared among studies.

Our study design differed from other studies of aquatic assemblages in urban streams in the use of a UII to define a gradient of urban intensity while limiting the variability of natural factors among selected basins within a region. The UII captures many of the complex stressors associated with urbanization that were unique to a study area and could have cumulative effects on aquatic assemblages. The design allows comparison of patterns of responses of aquatic assemblages to urban intensity among different geographic regions even when specific variables included in the UII differed. Other studies have used single measures of urban intensity to assess the effects of urbanization on aquatic assemblages. Degradation of aquatic assemblages was related to percent urban land (e.g., Kennen 1999; Diamond et al. 2002; Morley and Karr 2002; Roy et al. 2003; Snyder et al. 2003; Fitzpatrick et al. 2004), population density (e.g., Fitzpatrick et al. 2004), and impervious area (e.g., Booth and Jackson 1997; Wang et al. 2000, 2001; Sonneman et al. 2001; Morse et al. 2003; Ourso and Frenzel 2003; Taylor et al. 2004).

Impervious area (effective and total) has emerged as a key indicator of urbanization (Arnold and Gibbons 1996) that has been widely used to associate urbanization with changes in aquatic assemblages (Klein 1979; Pratt et al. 1981; Duda et al. 1982; Whiting and Clifford 1983; Pedersen and Perkins 1986; Jones and Clark 1987; Garie and McIntosh 1986; Maxted and Shaver 1997; May et al. 1997; Wang et al. 2000; Paul and Meyer 2001; Walsh et al. 2001; Center for Watershed Protection 2003; Morse et al. 2003; Ourso and Frenzel 2003; Taylor et al. 2004). It is an ecologically appealing indicator of urbanization because it bears a direct relation to runoff and its effects on transport to the stream (e.g., litter, sediments, microbes, nutrients, organic matter, surfactants, heavy metals, pesticides, hydrocarbons), transport within the stream (e.g., rates of downstream transport and exchanges with floodplains and riparian areas), and hydrology and instream habitat (e.g., changes in frequency and severity of extreme flows, changes in sediment transport, changes in channel geomorphology). Unfortunately, the measurement of impervious surface is not a trivial task, particularly over large areas, and most estimates are totally or partially dependent upon applying conversion factors to land-use or land-cover data. The national land-cover data (U.S. Geological Survey 2002) that were available for our urban studies did not include estimates of impervious surface area. We estimated impervious surface area by applying conversion factors to land-cover data (McMahon and Cuffney 2000). However, when we examined the relations between these estimates of impervious surface and UII, we found very strong correspondence (BOS: $Y = 0.445X + 0.4143$, $R^2 = 0.96$; BIR: $Y = 0.5406X + 0.9799$, $R^2 = 0.98$; SLC: $Y = 0.4267X + 2.9513$, $R^2 = 0.95$; where X = UII, Y = % impervious surface) due to the underlying mathematical relations with land cover. Consequently, estimated impervious surface area did not provide any additional explanatory power beyond that of the UII and was dropped from subsequent analyses in favor of variables that were directly measured from census data and remote-sensing images.

Many studies have demonstrated an adverse effect on aquatic assemblages when impervious area in a basin area reaches anywhere from 5% to18% (Klein 1979; Pratt et al. 1981; Duda et al. 1982; Whiting and Clifford 1983; Garie and McIntosh 1986; Pedersen and Perkins 1986; Jones and Clark 1987; Maxted and Shaver 1997; May et al. 1997; Wang et al. 2000; Paul and Meyer 2001; Walsh et al. 2001; Morse et al. 2003; Ourso and Frenzel 2003; Taylor et al. 2004). Using the equations (UII versus % impervious surface) described above for each study area, adverse effects on aquatic assemblages would be expect to occur between UIIs of 10–40 in BOS, 7–35 in BIR, and 5–35 in SLC.

The scale at which urbanization affects aquatic assemblages can vary depending on the geographic setting, the scale at which urbanization is most intense, and the range of that intensity. Our design was set up to minimize the local-scale effects (e.g., habitat) and maximize the detection of basin-scale effects of urbanization. In the Puget Sound basin (Washington, USA), macroinvertebrate assemblages as measured by a benthic IBI responded to changes in land cover at the basin and local scales (Morley and Karr 2002). Similarly, Roy et al. (2003) found strong negative relations between basin land-cover and stream macroinvertebrate indices in Georgia streams (USA); however, biotic indices were better predicted by reach scale variables than single, basin-scale land cover. In contrast, diatoms were better indicators of nutrient enrichment, whereas macroinvertebrates were better indicators of basin-scale urban disturbances in Melbourne, Australia streams (Sonneman et al. 2001; Walsh et a. 2001). Fish assemblages in Opequon Creek watershed, West Virginia, USA were strongly associated with the extent of urban land use in the basin; however, urban land use was more disruptive to fish assemblages in basins with steeper channel slopes (Synder et al. 2003).

Many factors can be associated with urban disturbances, which makes it difficult to predict how ecological components will respond to specific aspects of urbanization, particularly in different geographic locations across the United States. The value of the UII versus other urban disturbance measures (e.g., single variables used in the index, impervious area, population density) of urban disturbance that affect aquatic assemblages, physical habitat, and water chemistry responses awaits further evaluation. The UII might be used instead of single or multiple measures of urban disturbance, once associations between the index, individual stressors, and aquatic assemblages are established.

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